# TITAN - THE ULTIMATE DESTINATION FOR AEROBOTS

**Julian Nott**
*Consultant Scientists, Santa Barbara CA 93103 USA, ScienceConsulting@nott.com*

**ABSTRACT** *TITAN: NOT GOOD, PERFECT*

Aerobots, robotic balloons and blimps have been proposed for exploring Titan for many years. However what is not appreciated is that Titan is not merely a place where aerobots are possible but rather has better conditions for aerobots by several orders of magnitude than any other location in the entire solar system.

The low gravity and a dense atmosphere are obviously helpful. But the thermal environment and fabric life, both dominant considerations in the design of balloons and blimps are orders of magnitude better than on Earth. This means aerobots can fly for years or decades over Titan, limited only by the weather. And entirely new configurations are possible such as Montgolfier "Infinity Balloons" lifted only by surplus heat from radioisotope power sources.

This paper looks at the conditions in detail and proposes several new kinds of aerobots.

## 1. TITAN: EXTRAORDINARY POSSIBILITIES

Aerobots, robotic blimps and balloons, were first proposed for Titan in 1978 by the remarkable Jacques Blaumont. Alan Friedlander wrote a detailed proposal for a Titan balloon in 1986 [1]. Even before the Huygens probe landed on Titan, aerobots appeared very suitable, see for instance the comprehensive 2004 paper Hall [2]. But with Cassini, Huygens, Keck and other data, Titan emerges as not only suitable for aerobots but, in almost every regard, orders of magnitude better than any other Solar System destination. Aerobots are not merely suitable for Titan: Titan is their perfect home.

Basic factors are all ideal. Gravity is low and atmospheric density very high. Surface winds, the bane of all buoyant craft, appear to be very light.

But critical factors are dramatically better. Firstly the change in solar heating between day and night is usually the single most important factor for terrestrial balloon designs. But below Titan's clouds this factor is so small as to be unimportant. Second, ultraviolet and diffusion limit the life of existing balloons but are vastly reduced on Titan. A third and crucial factor is the low temperatures. For terrestrial balloons the majority of heat transfer is by thermal radiation. But radiation obeys Stefan's Law, depending on the fourth power of absolute temperature. Titan's temperature is so low that radiation is very small so another critical factor for terrestrial balloons is vastly more favorable. This alone opens up novel possibilities. Finally the dense atmosphere and low absolute temperature mean that change in lift gas temperature generate much greater change in lift than for terrestrial equivalents. This is summarized in Fig 1.

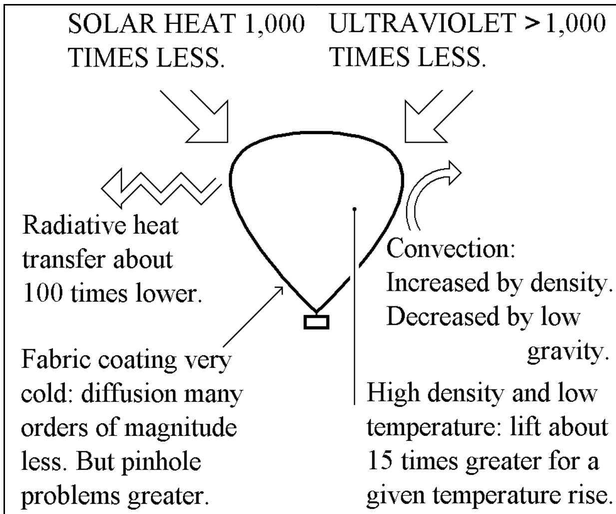


Fig 1. Dramatic decrease of factors important to balloon design on Titan relative to Earth.

While surface rovers move precisely, the terrain they can cross is limited. Even if rovers could operate on Titan's surface, their range is limited. While aerobots have less precise control, they can cover great distances: a craft could alternate between flying near or even touching the surface, and flying at altitude to move substantial distances in upper winds. Wind steering, steering only by changing altitude has become well developed and is useful for any aerobot. Balloons are less maneuverable than blimps but can still make many kinds of observations. And their remarkable simplicity implies great reliability

These factors permit extraordinary possibilities. The most striking is that a radioisotope power source, RPS, provides enough "waste" heat to fly Montgolfiers, "hot air balloons". Such craft could be very simple with corresponding high reliability and could fly for years or decades.

## 2. THERMAL CONDITIONS & HEAT BALANCE

The temperature of the lifting gas is fundamental to the behavior of any balloon so understanding heat transfer is essential to design and operation.

### 2.1 Day / Night Variation

For most terrestrial balloons by far the most important factor limiting the length of flight is solar heating. When the sun heats a classic balloon the gas and expands and gas must be vented. When heating stops, the gas lost must be made up by ballasting. Designers have been trying to overcome this fundamental limitation throughout the two hundred and twenty years of ballooning. Many concepts have been proposed including controlling gas temperature [Rozier Balloons] and making up lift with cryogenic helium [AN balloons]. These types work well but have specific limitations. Preventing expansions of the gas [Superpressure Balloons such as GHOST and ULDB] appear attractive but no design has yet been fully successful except very small versions, several of which have flow for two years.

But below Titan's clouds the incident energy from the sun is a thousand times less than on Earth. Instead of being the dominant factor in balloon design it becomes almost insignificant.

### 2.2 Thermal Radiation

Another startling difference concerns thermal radiation. With terrestrial balloons radiation typically accounts for two thirds or more of the heat transfer. This is not just for hot air balloons: in designing high altitude helium balloons, convection is often neglected completely. Radiative heat transfer can be estimated with some confidence from first principles because it obeys Stefan's law. Since the law involves the fourth power of the absolute temperatures, it is self-apparent that radiative heat transfer in the Titan environment will be extremely small compared to Earth.

As with solar heating, at Titan thermal radiation goes from a factor that dominates design to a minor concern.

### 2.3 Convection & need for physical modeling

With low radiation, the main heat transfer mechanism between the lifting gas and the environment will be convection. Unfortunately numerical modeling of free convection is difficult. For reliable estimates it will be essential to make measurements on physical models. A model could be of similar size to an actual Titan craft reducing scaling concerns. Titan's low gravity reduces buoyancy forces, which will reduce convection. Experience shows that simple model balloons can be very useful. And modest models can be very valuable in exposing unforeseen problems at very low cost. The author has used physical models three to five meters in diameter to develop heat transfer software, Fig 2. This software works with full sized balloons and has proved central in allowing the author to set 79 world ballooning records and valuable for many other projects.

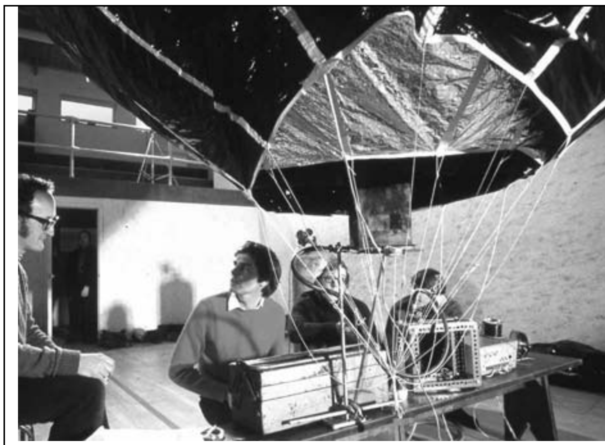

Fig 2. The author has made wide use of instrumented models. This is a double-hulled Montgolfier balloon.

## 3. EXTRAORDINARY FABRIC BEHAVIOR

Nearly all the critical processes that limit fabric life for buoyant craft are not merely better on Titan, but orders of magnitude better than on Earth.

### 3.1 Fabric: ultraviolet & chemical deterioration

Ultraviolet it is very damaging to terrestrial balloons. But below Titan's clouds sunlight is a thousand times less intense than on Earth. Shorter wavelengths are scattered even more by Titan's atmosphere so ultraviolet will be even more attenuated. The longest flights by terrestrial balloons, in strong ultraviolet at 12,000 meters altitude, exceed 2 years. With a thousand times less intensity, a Titan balloon's fabric should not fail from ultraviolet for 2,000 years!

Damage by ultraviolet depends on the energy of individual photons and is proportional to intensity. But many chemical processes depend on thermal activation energy and their speed halves with every 10K drop in temperature. Between 60C, a typical hot air balloon fabric temperature, and Titan's 90K, reaction speeds will fall by many orders of magnitude and many chemical processes will be insignificant.

Discoloration of terrestrial balloons over time is a concern because more heat is absorbed from the sun. But if fabrics darken by chemical processes or the accumulation of organic compounds, this will not matter over Titan because solar heat is so small.

### 3.2 Gas diffusion & pinhole leaks

Like the chemical processes referred to in the previous section, diffusion of helium through fabric is controlled by thermal activation energy and similarly drops by orders of magnitude at Titan temperatures. It will not be important even for small balloons, Fig 3.

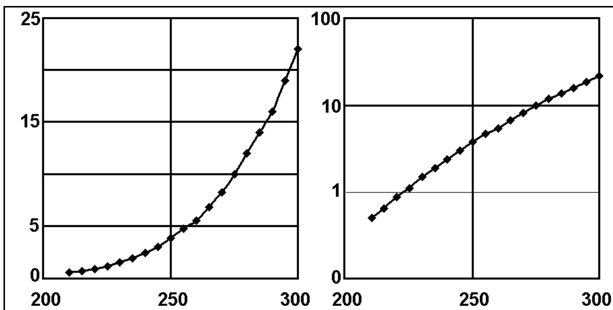


Fig 3. Left, relative permeability of helium through Mylar, 210K to 300K, right with logarithmic scale.

BUT THIS DOES NOT APPLY TO PINHOLES, which are likely to be significant for long-life Titan aerobots. Indeed one of the few factors that will be worse on Titan is that any fabric coating will be stiffer and more prone to pinhole formation.

But this might be solved by completely reconsidering coating materials. Some materials are not considered for balloons because they do not hold gas well at room temperatures. But with reduced diffusion at Titan temperatures they might have adequate gas holding. Simultaneously mechanical properties might be better than conventional materials. Silicones come to mind: they do not hold gas well at terrestrial temperature but on Titan might hold gas adequately. And they have excellent mechanical properties at low temperature. It would be valuable to review materials popular in the cryogenics industry from this perspective.

## 4. TOPOGRAPHY

In light winds terrestrial balloons can easily negotiate up and down across steep terrain: "Contour Flying" is a popular pilot pastime. Gradients that are impossible for surface rovers are no barrier to Aerobots. The “Highlands Region” about 5 km North of the Huygens landing looks impassable to rovers. But these steep valleys may often have light winds making them ideal for aerobot visits, and scientifically interesting material have likely washed into them.

The highest terrain has to be considered: the height of Olympus Mons is significant for Mars balloons. But if Titan is similar to Ganymede with maximum elevations of a few thousand meters, this is not a concern.

## 5. WEATHER VERSUS CLIMATE

With the ubiquitous cloud cover and haze, solar heat at Titan’s surface is modest suggesting benign conditions. On earth there is nothing a balloon pilot likes more than full cloud cover because tranquil conditions can be expected.

But almost the first thing a designer considered for any lighter than air project is not climate but weather, wind, rain, turbulence, lightning, microbursts, aggressive wave, drafts: there is a very long list. No aircraft, even the most robust fighter jet, can survive all weather on Earth. Long flights over Titan need a meticulous understanding of weather extremes and strategies to avoid them.

A simple example of weather extremes can be found near Pasadena at the famous Tustin Blimp Hangars, an important lighter than air center. They are in an ideal location with year-round average winds of merely 1.9 meter per second. Nonetheless, gusts routinely exceed 20 meter per second and the strongest gust in the last twenty years exceeded 30 meters per second.

### 5.1 Extrapolation from terrestrial experience

Titan’s weather has clear similarities to Earth, including convection, possible highs and lows, and the methalogical cycle. Several tens of millions of weather balloons have sounded the earth's atmosphere, yet new weather features are constantly observed. By contrast there has been one sounding of Titan's atmosphere by Huygens. It is essential to be careful extrapolating, but there is much to learn from terrestrial balloon experience. Several meteorologists now have a brilliant understanding of how weather influences balloons, combining a great depth of scientific knowledge with long practical experience. It would be valuable to involve them in any Titan aerobot project at an early stage.

Unusual winds sometimes occur in valleys and balloon meteorologists have a unique understanding of them.

**5.2 Wind Steering**

These same meteorologists understand “wind steering”. Remarkable success is now achieved steering balloons solely by changing altitude to enter favorable winds. Skilled pilots can arrive within a meter of a pre-assigned target after flying ten kilometers. Sport balloons routinely cross the continental United States using wind steering alone, yet avoid mountains, bad weather and prohibited areas. Of course they use vast meteorological services. But the understanding learned on earth could be useful on Titan where goals could be much simpler, such as remaining in a particular hemisphere or avoiding areas of convection.

Wind steering is not restricted to balloons. It can be very valuable for blimps. A balloon can only climb or descend at its exactly location limiting the winds it can enter. But a blimp can move under power and potentially moving a short distance may allow it to be enter significantly different winds.

A Titan craft must use wind steering autonomously. Ever more structure, particularly variations in wind direction with modest changes in height, is constantly discovered in the Earth’s winds and similar structure seems likely over Titan. It is possible an aerobot might navigate with simple instructions such as "Cycle altitude slowly until you find a wind with a component towards the Equator. When you find it fly level". This could only be fully tested in situ over Titan. But the instruments, controls and processing likely to be included in any aerobot would allow this to be attempted with no penalty except the cost of programming the instructions.

**5.3 Icing and Rain**

It is generally believed that some long duration balloon in the GHOST and EOLE programs were bought down by icing. Flying at levels below those at which methane melts, icing is not a problem. And if a balloon descends as soon as it collects light icing it will likely melt at lower levels.

**6. AEROBOT TYPES: INFINITY BALLOONS**

Balloons for Titan can be designed with well-established fabrics. And interesting new fabrics being developed for stratospheric blimps may be very useful.

Since others have covered blimps in detail, these notes focus on balloons. It appears that Montgolfier and Rozier balloons heated only by the surplus heat from an RPS could fly over Titan for years or even decades. Nothing lasts forever: nonetheless the name INFINITY BALLOON has been coined for any balloon able to fly much longer than a terrestrial equivalent.

Looking at these in detail:

**6.1 Montgolfier Infinity Balloon**

A Montgolfier balloon has great advantages. It does not need helium for inflation. Numerous pinholes in the fabric are of no importance. The fabric does not flex when changing altitude so it can wind steer indefinitely without reducing fabric life. The only movement will be in gusts or turbulence or when the gondola touches the surface. Assuming the communication antenna has no moving parts such as a phased array, the only moving part in the craft is a control valve. A very simple valve is needed to control balloon temperature. This could take several forms. The valve does not even need to seal tightly when closed: minor leakage is not important. With these fabric advantages and extreme mechanical simplicity such balloons could fly for extraordinary periods.

This type of balloon has the greatest flexibility to descend to the surface repeatedly. Some designers have been reluctant to consider allowing a balloon gondola to touch the surface. However in light winds it is common practice in sport balloons to make "intermediate landings" on the surface to change passengers or take on fuel. As Titan conditions become better understood, there seems no reason why balloons should not touch the surface repeatedly. Presumably the largest, most interesting organic molecules are on the surface.

**6.2 Double-hulled and double-gored Montgolfiers**

An excellent way to improve the performance of this type of balloon is to use an envelope with two layers. A variety of multi-layer envelopes have been used for specialist balloon projects over many years.

The simplest arrangement is to fly one balloon inside another, a double-hull. This allows for a large gap giving good installation.  But for a number of reasons the most suitable for Titan is probably a balloon with double gores.  This is a balloon with a single set of vertical load tapes but with two layers of fabric.  Both layers meet at the tapes but there is a gap in the centre center of the gore.  The installation is less effective but there are important operational advantages.

The author has designed and built both double-hulled and double-gored balloons.

**6.3 Quantitative estimate of heat loss**

The author has developed mathematical models over many years to estimate heat transfer for balloons. These are well tested in the terrestrial environment and are central to the author's successfully establishing 79 world balloon records.

These models have been used for the preliminary design of a Titan Montgolfier Infinity Balloon. As explained is section 2.2 thermal radiation can be estimated from first principles with some confidence and is clearly very low compared to terrestrial balloons. But convection is much more problematic.  Keeping this caution in mind these models show that it is well within the capability of an RPS to heat this kind of balloon.

A practical Montgolfier must be have more heat than is needed for level flight, particularly to stop a decent. Further modeling is needed but it appears radioisotopes can provide sufficient heat.

**6.4 Rozier Infinity Balloon**

The author CURRENTLY believes that a Montgolfier Infinity Balloon is the best approach.  However new data about Titan is pouring in from Cassini.  If weather conditions are not tranquil enough for a Montgolfier, for the same payload a Rozier is substantially smaller and better able to survive weather hazards.  A Rozier, a combination balloon, gets most of its lift from hydrogen or helium but controls altitude by regulating the temperature of this gas.

Minor fabric damage is not significant for Montgolfiers but even pinholes will cause significant gas loss for a Rozier.   Pinholes are a universal concern for balloon especially with light fabrics.  In a Rozier the fabric flexes with every change in altitude, encouraging pinhole formation.  But it is still better than a blimp that constantly pitches and rolls.  The shape of the ballonets in a blimp is always a compromise but the ballonet or ballonet equivalent in a Rozier can be symmetrical with smoother motion.

Any valve to control gas must seal meticulously, always a concern for long-term operation.

**6.5 Quantitative thermal analysis**

Because incident sunlight is so weak, the heat absorbed by a Titan Rozier will only be tens of watts.  So at night only tens of watts are needed to maintain the temperature of the lifting gas and hence maintain level flight, likely a small fraction of the heat from an RPS.

**6.6 Superpressure Balloons**

Superpressure balloons have flown for over two years, about 20 times longer than any other type.  But only a few balloons from a large fleet managed achieved this. The others were presumably brought down by weather, pinholes or fabric deterioration.  In principle Titan superpressure balloons could fly for astonishing periods.  But they must remain free of pinholes and avoid bad weather, both major challenges.

The drawback of superpressure balloons is that they cannot change altitude for wind steering or to reach the surface for observations.

Various superpressure types have been flown which incorporate compressors to allow flight at different levels.  These include the pumpkin balloon the author designed and piloted, making the first balloon crossing of Australia.  A promising new development is the Voss CMET, **C**ontrolled **MET**eorological balloon. Although any compressor is only needed when changing altitude, it is still a reliability issue for very long flights. Also when altitude changes the fabric flexes introducing pinhole concerns.

**6.7 Launch**

A novel method of launching aerobots which might minimize pinhole formation is described in a companion paper "Ballutes: Launching Aerobots Without Compromises". [3]

**7. IMPROVING USEFULNESS & SUCCESS**

**7.1 A fleet**

When the next mission goes to the Saturn system, understanding of Titan's weather will still be incomplete, so there is a strong case for sending a fleet, perhaps one large craft and several much smaller “pilot balloons”. Presumably many very interesting scientific opportunities are on the surface. With only one craft there would be reluctance to take even small risks by flying low. With a fleet, the loss of a small balloon would be disappointing but not disastrous and subsequent operations would learn from the mishap.

### 7.2 An orbiter

An orbiter enormously enhances the possibilities for Titan aerobots. High data rates would be possible with much lighter, low powered communications equipment. Much smaller balloons would be viable. As an example of what is currently possible based around commercial components, Paul Voss’s long duration CMET balloons include a pumping system for altitude control and a two-directional Iridium satellite link all in craft with a total mass of 750 grams. [4]

An orbiter would be invaluable for balloon location, function exactly as the terrestrial ARGOS system.

### 7.3 Accidental ground contact

Any aerobot gondola should be able to survive accidentally hitting the ground. This is a common and harmless occurrence with sport balloons.

### 7.4 Operation after landing

Any aerobot is likely to land before its RPS stops providing any power. Aerobots should be designed to operate after landing. Titan would be left with a long-lasting weather station[s] that would provide invaluable data for third generation Titan explorers. Even if an aerobot envelope tears in flight, the low gravity and thick atmosphere will mean a low terminal velocity. It should be possible to design components to survive the impact.

## REFERENCES

1. Friedlander, Alan L., “Buoyant Station Mission Concepts for Titan Exploration,” Acta Astronautica, Vol 14, pp 233-242, 1986.

2. Hall J. L, Kerzhanovich, V.V, Yavrouian, A. H., Jones, J.A. et al “An aerobot for global in situ exploration of Titan” 35th COSPAR Scientific Assembly, Paris, France, 2004.

3. Nott, J, IPPW 4 2006, "Ballutes: Launching Aerobots Without Compromises".

4. Voss, P.B., E.E. Riddle, and M.S. Smith, Altitude Control of Planetary Balloons, American Institute of Aeronautics and Astronautics (AIAA) Journal of Aircraft, 43 (2), 478-482, 2005

## ACKNOWLEDGMENTS

The author would particularly like to thank Dr James Rand, Winzen Engineering, Jack Jones, NASA Jet Propulsion Laboratory, Eric Frische, Space Data, and Luke Brooke, Tensys.